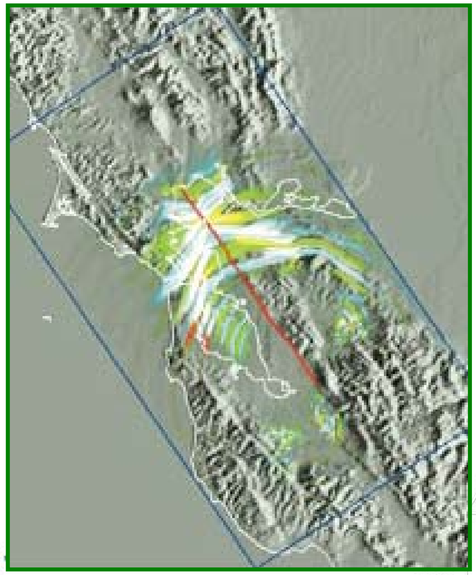
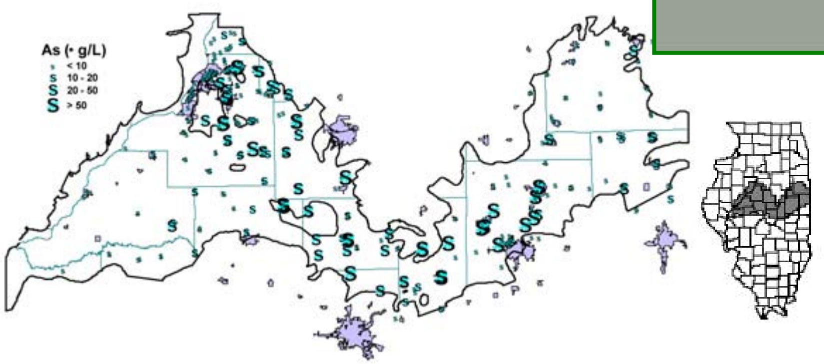
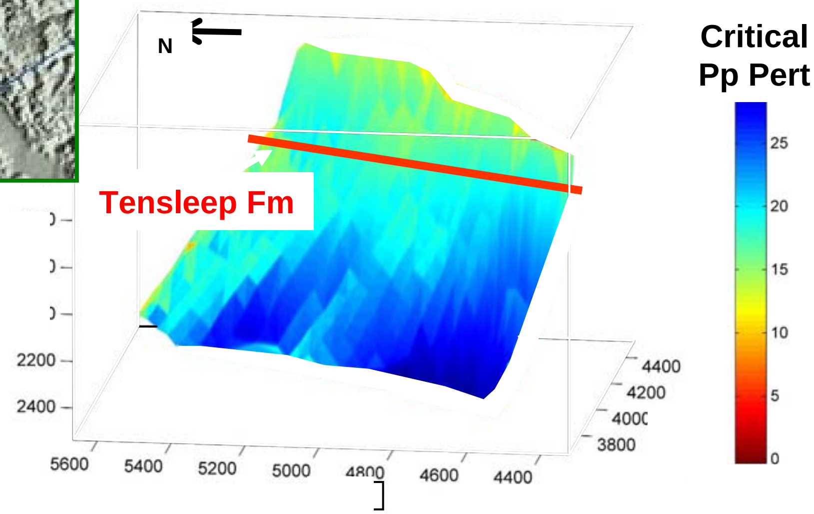
Operational protocols for geological carbon storage and a new hazard characterization approach





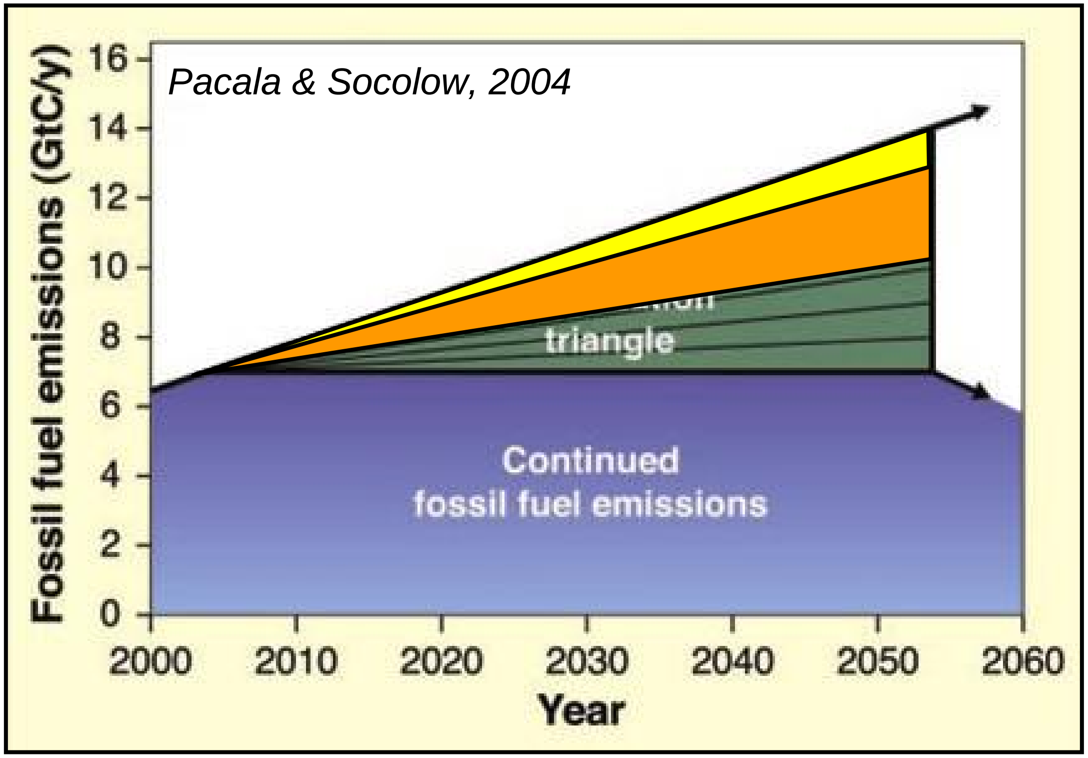


S. Julio Friedmann

Director, Carbon Management Program
Energy & Environment Directorate, LLNL

http://eed.llnl.gov/co2/

CO_2 Capture & Sequestration (CCS) can provide 15-50% of global GHG reductions

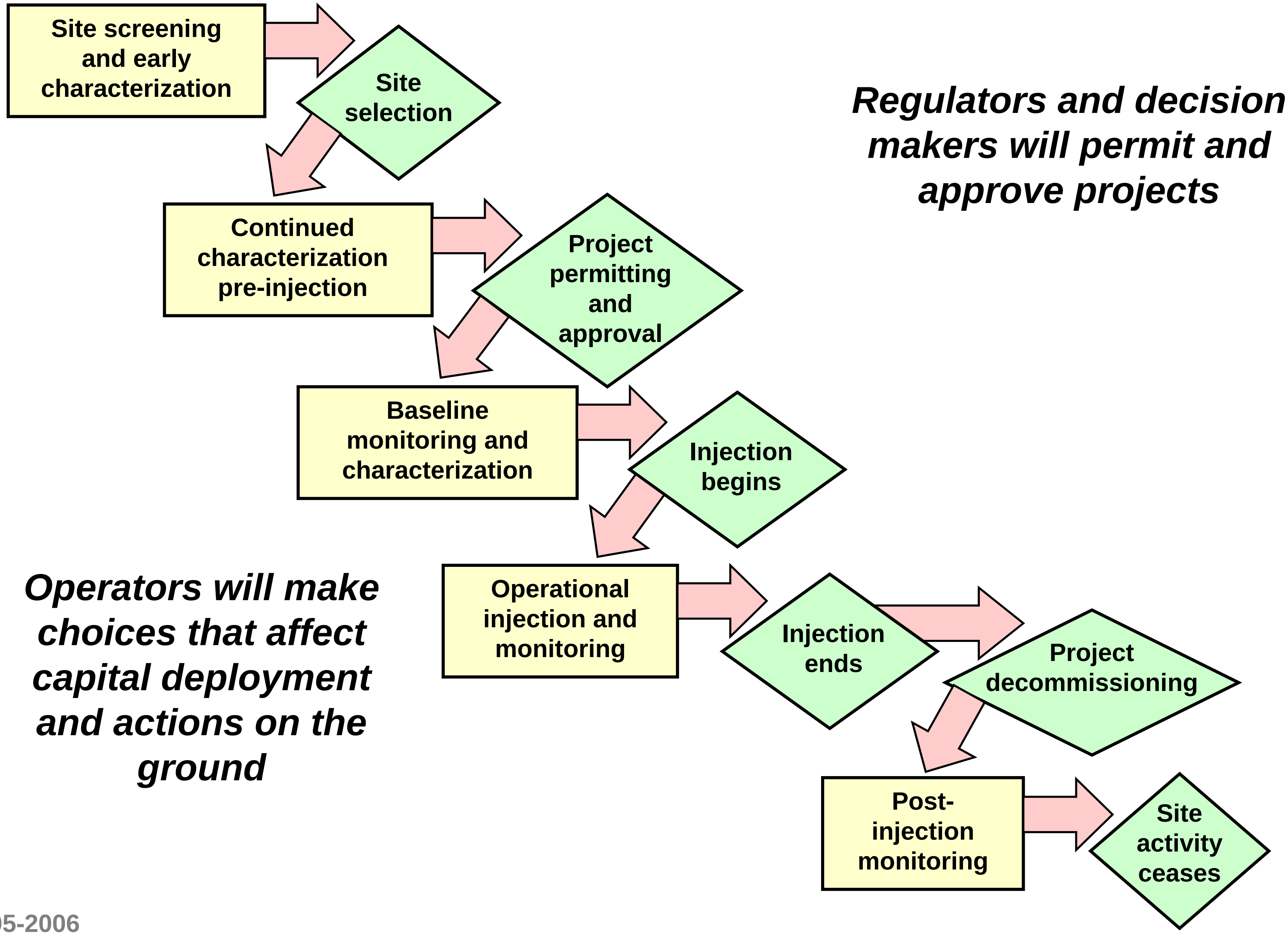


- **A key portfolio component**
- **Cost competitive to other carbon-free options**
- **Uses proven technology**
- **Applies to existing and new plants**
- **Room for cost reductions (50-80%)**

- ***ACTIONABLE***
- ***SCALEABLE***
- ***COST-EFFECTIVE***

This will require injection of very large CO_2 volumes a given site
- ***1 to 6 million tons/year***
- ***50 to 60 years***

Deployment of CCS is complex and will involve many tasks and decisions



Regulators and decision makers will permit and approve projects

Operators will make choices that affect capital deployment and actions on the ground

Why operational protocols?

CCS protocols help operators & regulators make decisions based on sound technical constraints across a range of geological circumstances

Protocols for CCS should help stimulate development of both commercial projects and evolving regulations

These protocols should also guide operators in terms of selecting and maintaining site effectiveness, esp. regarding key hazards and risks

Protocols should be FAST –
Flexible, Actionable, Simple, Transparent

The focus for operational protocols should be HAZARDS first, RISKS second

HAZARDS are easily mapped & understood, providing a concrete basis for action

RISK = Probability * consequence

RISKS are often difficult to determine

- **Hard to get probability or consequence from first principles**
- **Current dearth of large, well-studied projects prevents empirical constraint**

Earth and Atmospheric Hazards

The hazards are a set of possible features, mechanisms, and conditions leading to failure at some substantial scale with substantial impacts.

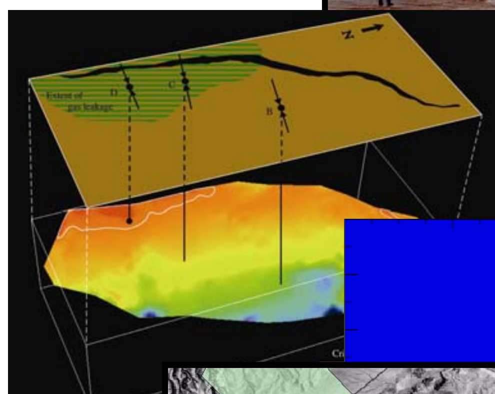
Atmospheric release	**Groundwater degradation**	**Crustal deformation**
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
		Induced seismicity
		Subsidence/tilt

Atmospheric release hazards could vent substantial CO_2 to the surface

Only under some atmospheric dispersion conditions, but require understanding of both likely cases and maximal tolerances

Well leakage

- Many possible processes, mechanisms
- Only a hazard if these processes lead to substantial venting

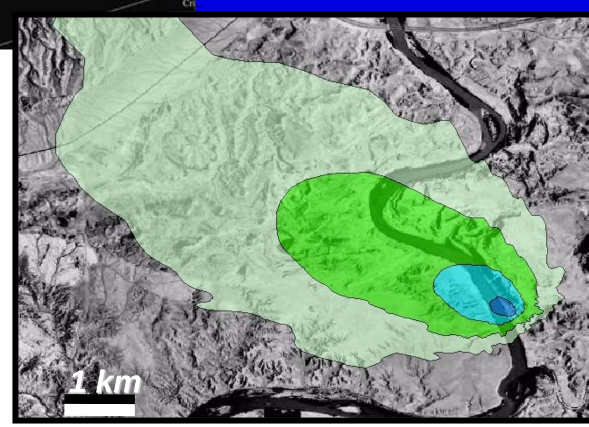


Fault leakage

- Likely to be slower flux and concentration than wells
- Focus first on extreme cases

Caprock leakage

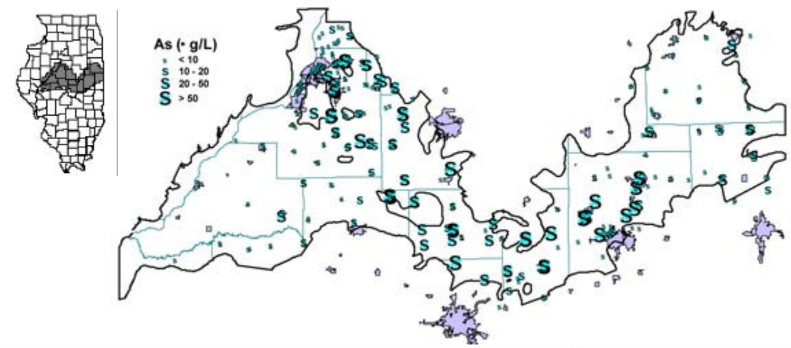
- Likely to be slower flux and concentration than faults or wells
- Focus first on self-reinforcing cases



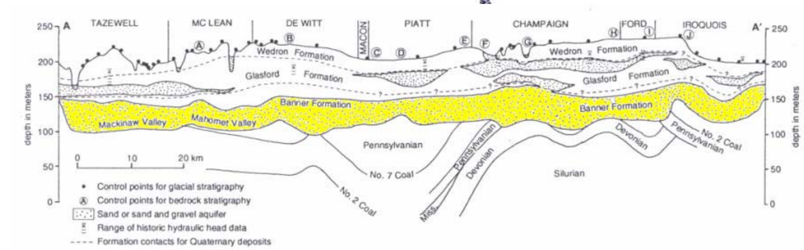
Pipeline/operational failure

Groundwater release hazards could result from substantial CO_2 release to shallow subsurface

Only some releases and groundwater aquifers will produce hazards of substance that require understanding of both likely cases and maximal tolerances



Well leakage
- Many possible processes, mechanisms
- Only a hazard if these it leads to substantial groundwater contamination



Fault leakage
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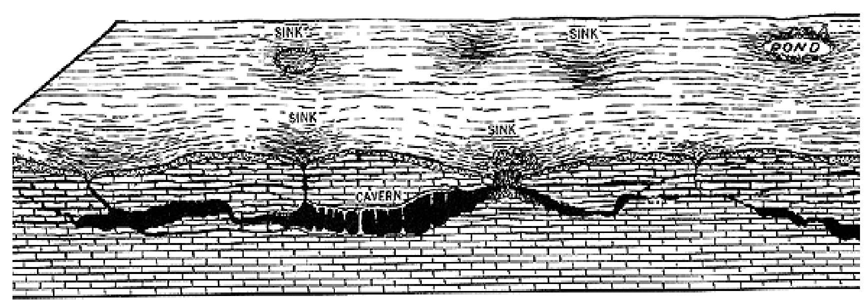
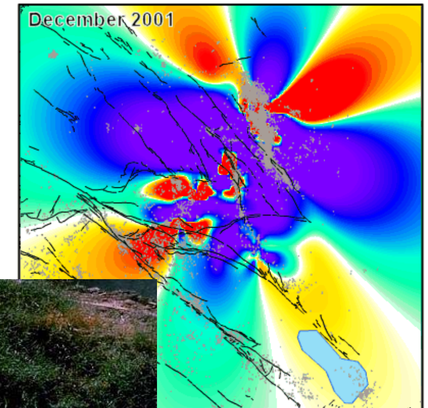


Karst development

Crustal deformation hazards result from geomech. responses to pressure transients and volume changes

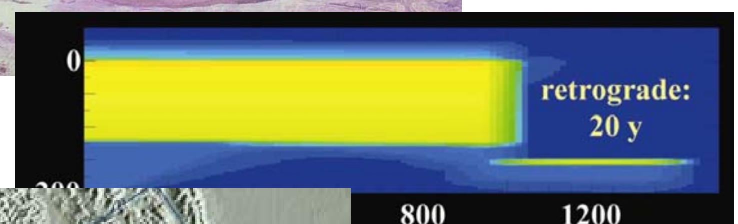


Induced well failure

- Mechanical failure leading to atmospheric/ GW hazards
- Potentially high cost element, EIS concern

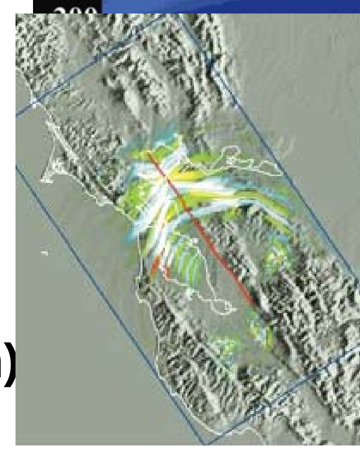
Fault slip/leakage

- May concentrate, increase flux
- May lead to well failure



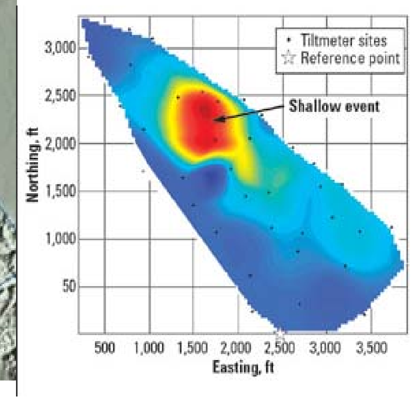
Caprock failure

- Focus first on self-reinforcing cases



Induced seismicity

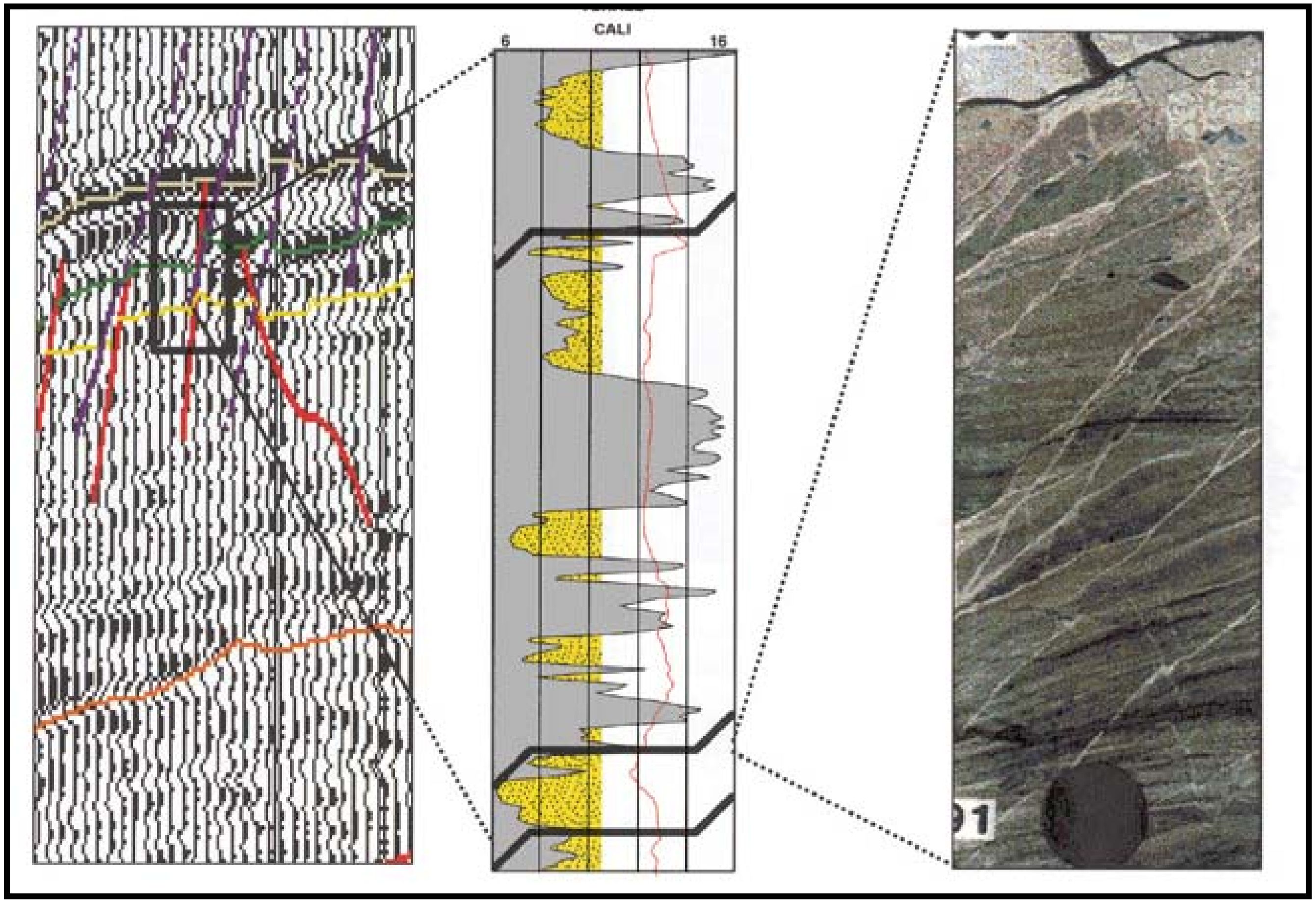
- Of great local concern (CA, CO)
- Highly sensitive to local conditions (in-situ stress, basin fill, fault size)



Subsidence and tilt

- Of great local concern (e.g., LB Aquarium)

Example of Hazards assessment: Fault-fluid transmission



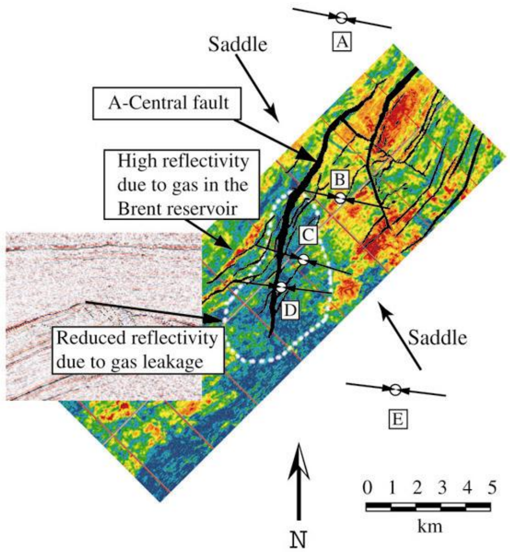
Leakage risk occurs at all scales; accurate characterization requires multiple data sets and detailed analysis.

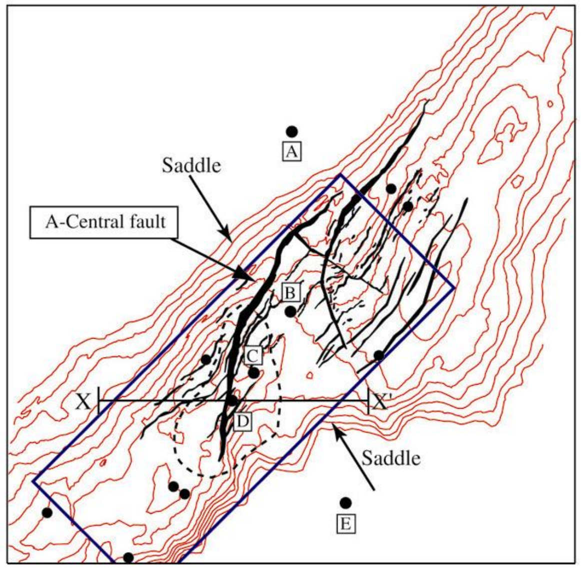
Seismic, well-log (esp. FMI), core, and production data (e.g. flow rates, pressure variations) are key to accurate risking of fault seal.

Given this complexity, hazard assessment must focus on large-volume fluid migration, flux determination & prediction, and induced slip

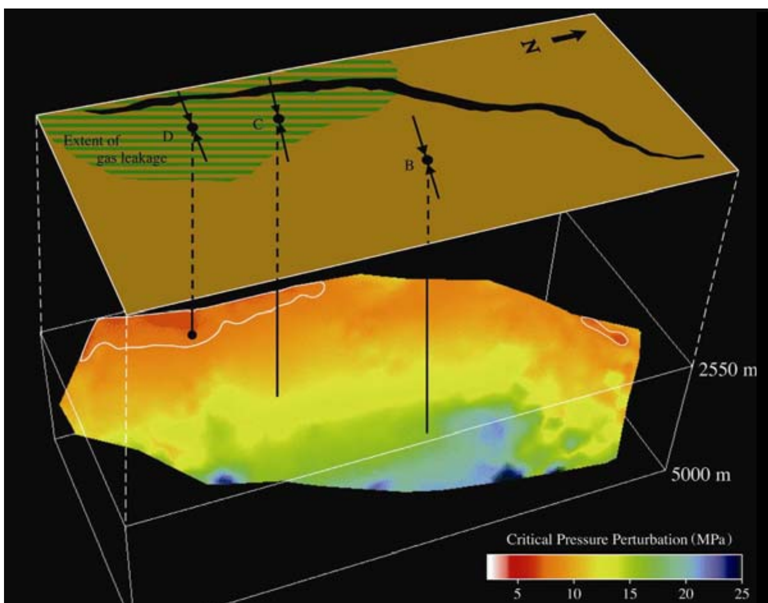
Wehr et al., 2000

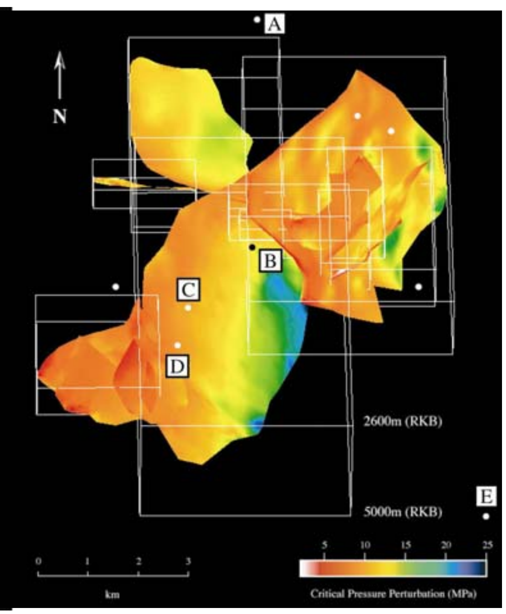
Fault reactivation & leakage hazards can be identified and managed w/ conventional tools





Fluid migration occurs with a high likelihood of fault reactivation. Zoback (Stanford) & his students use this method to predict reactivation pressure for individual faults and networks



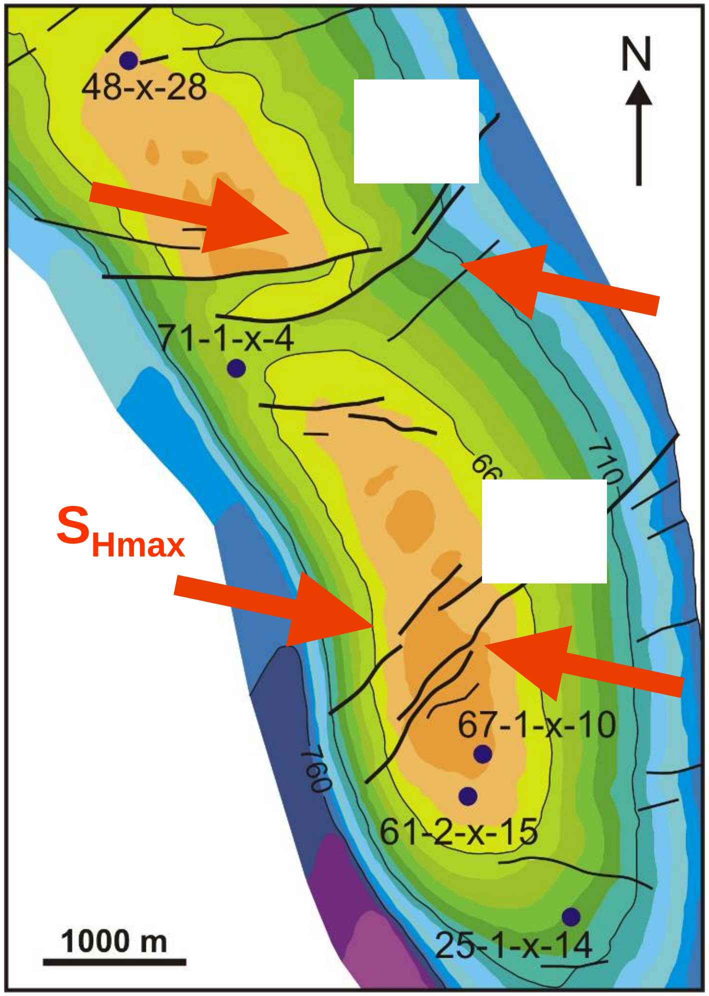


Function of geometry, orientation, pressure
- ***Good fault map (3D-seismic)***
- ***In-situ stress tensor (leak-off test)***

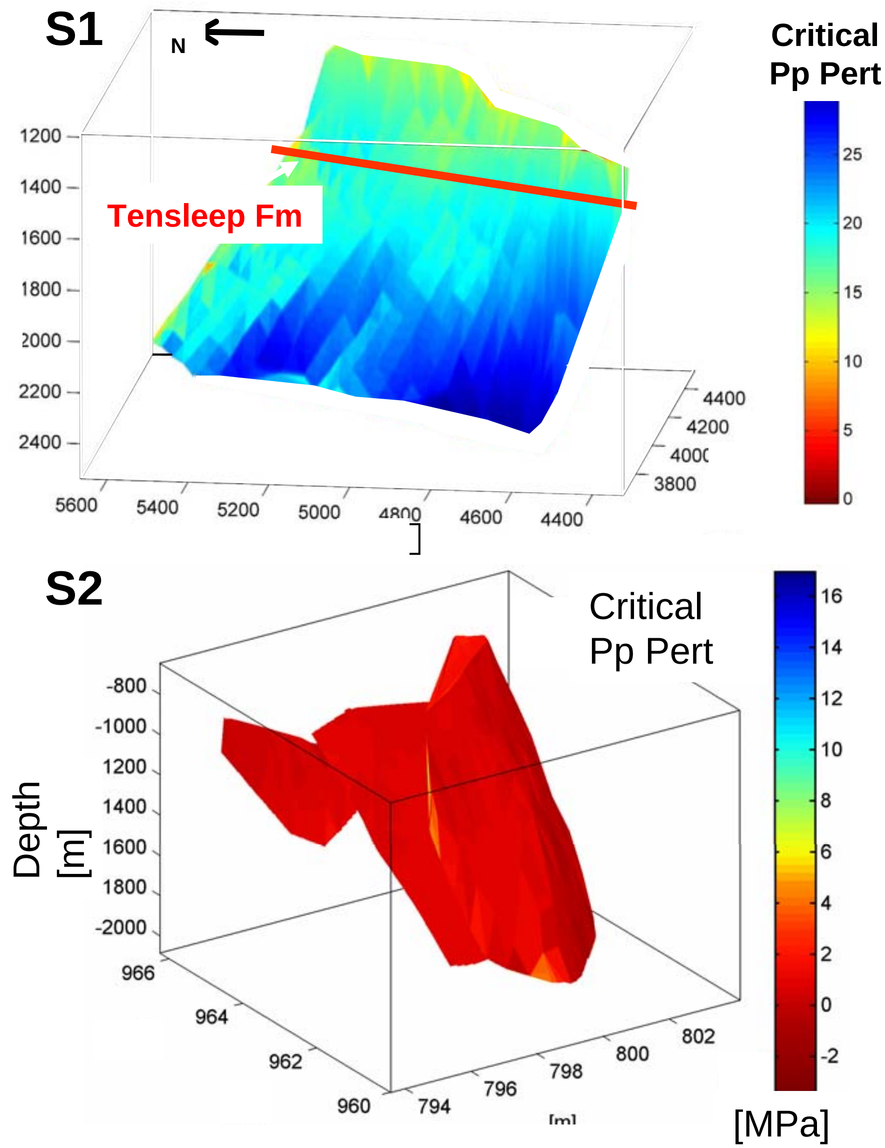
Easily calculated, Easily prevented

Wiprut & Zoback, 2002

Teapot Dome case illustrates sensitivity to geometry and stress (L. Chiaramonte, Stanford)



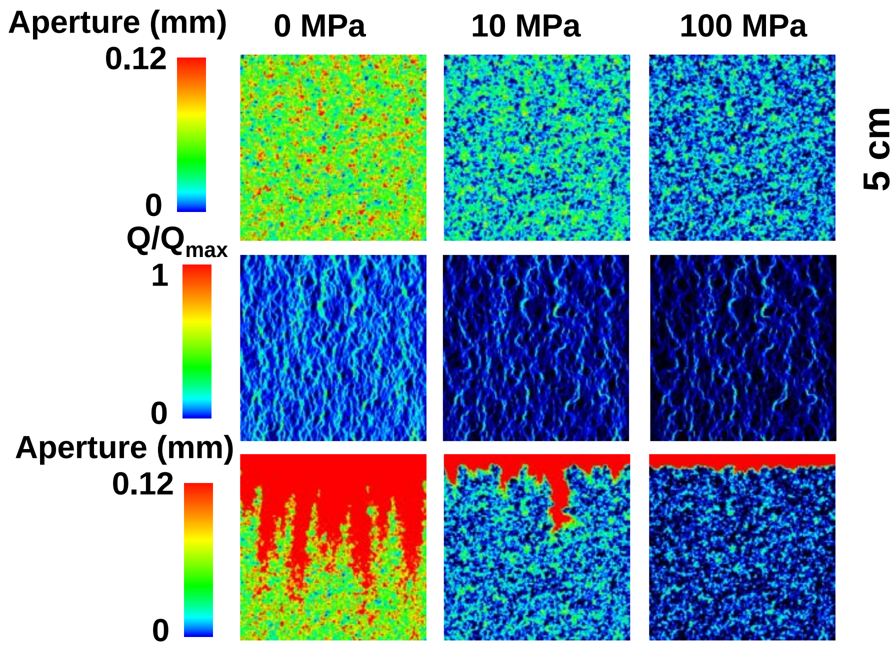
Time structure map 2nd Wall Creek Fm
(after McCutcheon, 2003)

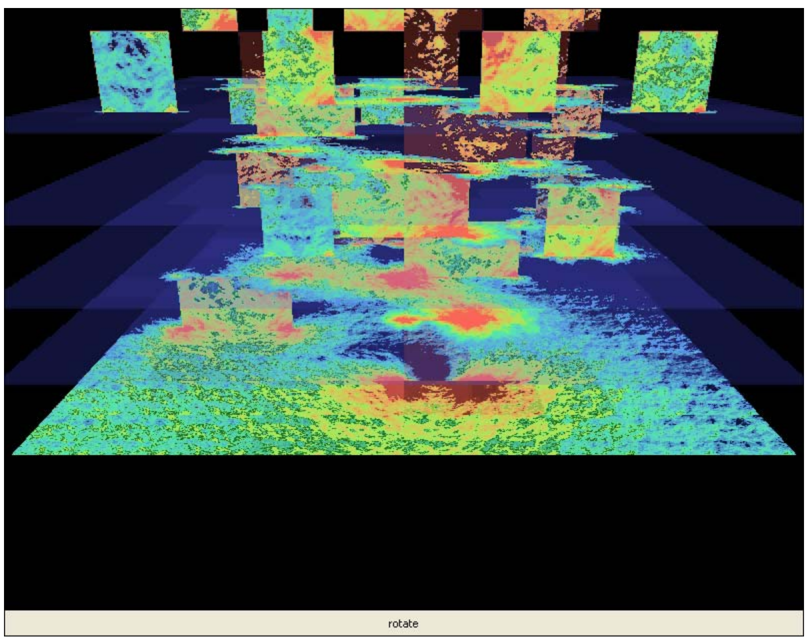


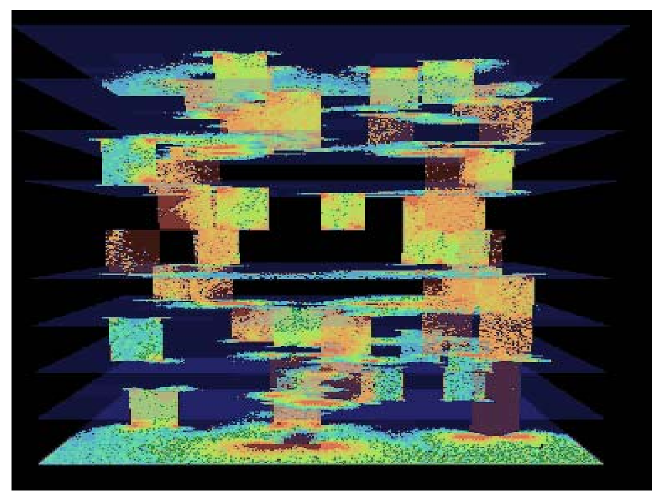
Fluid migration can be estimated with discrete fracture models and reactive transport

Coupled fluid-migration/ reactive transport in changing stress field can be simulated accurately

- ***Representative apertures for bounding analysis***
- ***Dynamic permeability field***
- ***Flux term calculated for pressure regime***





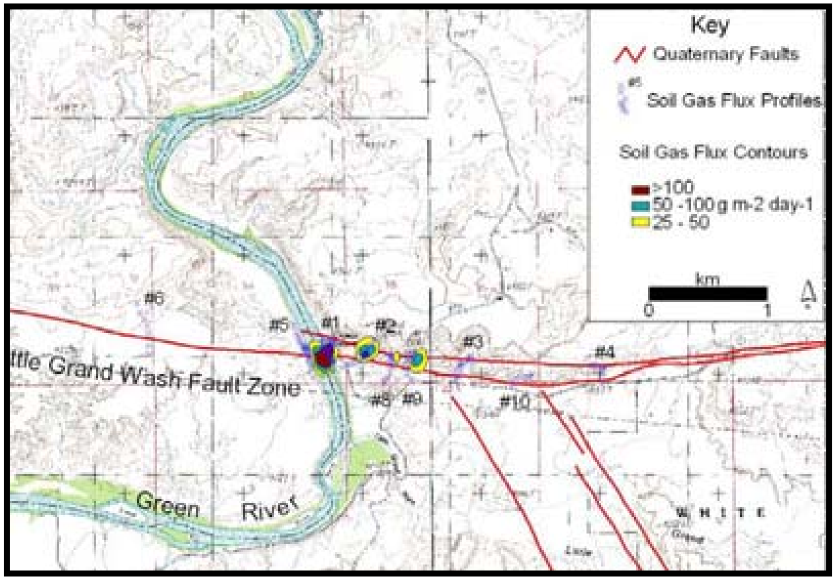


Little Grand Wash Fault soil surveys suggest fault leakage flux rates are extremely small

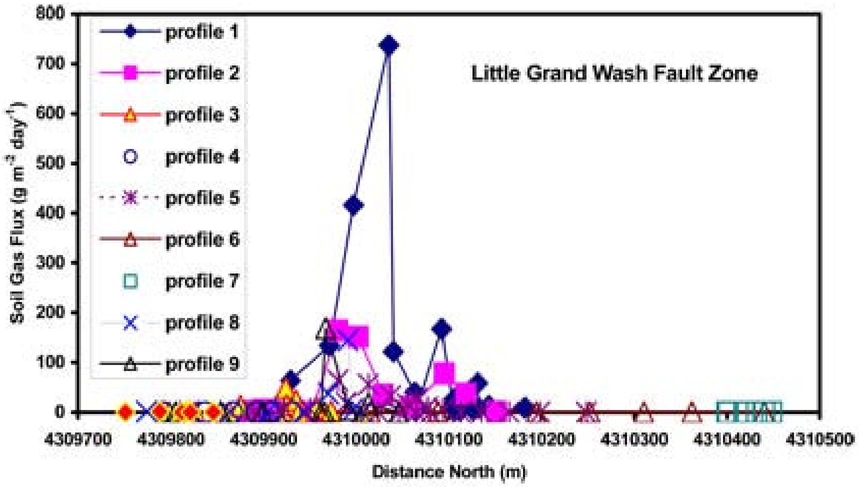
Allis et al. (2005) measured soil flux along the LGW fault zone.

Overall, concentrations were <0.1 kg/m²/d.

Integrated over the fault length and area, this is unlikely approach 1 ton/day.



At Crystal Geyser, it is highly likely that all fault-zone leakage is at least two orders of magnitude less than the well. At the very least, this creates a challenge for MMV arrays



Allis et al., 2005

Case I: Central Illinois Basin

General

- Many large point sources, some pure
- Large-capacity targets (29-115 Gt in SF)
- Solid geological knowledge

ICE components

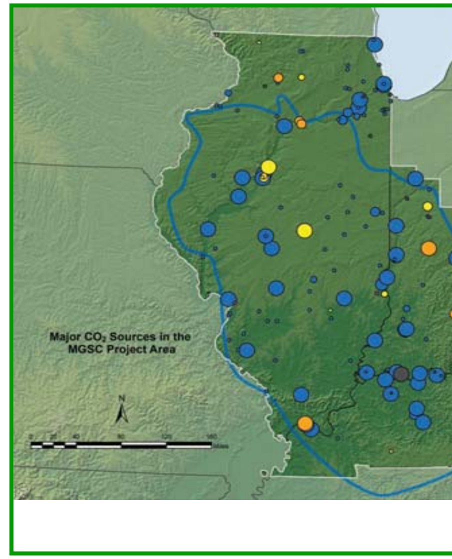
- Two main saline formations studied
  (Mt. Simon, St. Peters)
- O.K. injectivity, high capacity
- Evidence of effectiveness

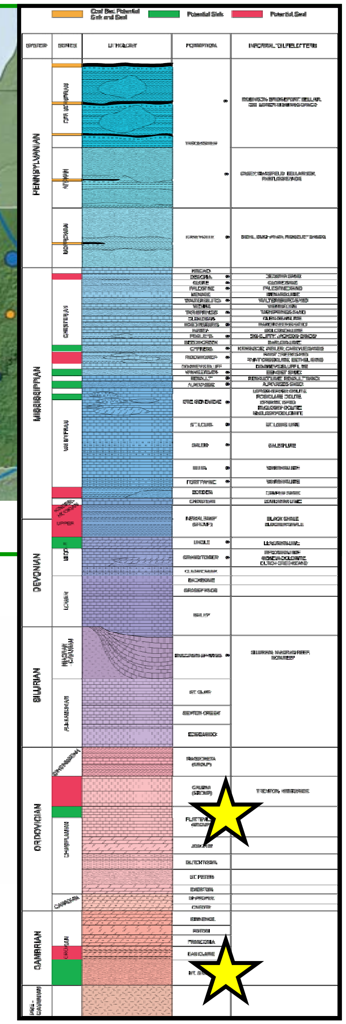
Central hazards

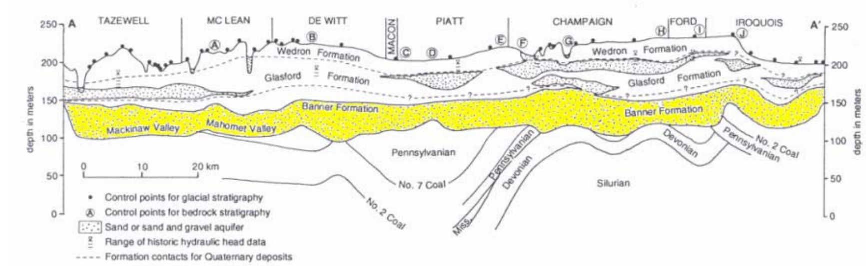
- Deep wells
- Unmapped faults
- Groundwater risks

Risk coefficients – mostly decrease

- Low population density
- Faults don't reach surface
- Very few wells into deep targets
- Effectively aseismic







Special thanks to the MGCS & Illinois State Geological Survey

Because of local nature of hazards, prioritization (triage) is possible for any case

Case 1: Illinois basin

Atmospheric release hazards	Groundwater degradation hazard	Crustal deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/ops leakage		
Pink = highest priority Orange = high priority Yellow = moderate priority		Induced seismicity
		Subsidence/tilt

Part of protocol design is to provide a basis for this kind of local prioritization for a small number of classes/cases

A protocol for central Illinois should focus on groundwater hazards from wells

Due diligence could be met through aggressive site characterization, targeted monitoring, and simple mitigation strategies

Atmospheric release hazards	Groundwater degradation hazards	Crustal Deformation hazards
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		Subsidence/tilt

Groundwater degradation

- Additional analyses needed?
- Mitigation strategy needed?

Well leakage and failure

- Maximum rates, under what circumstances?
- Maximum injection pressures?
- Deep wells intersecting sensitive groundwater areas?

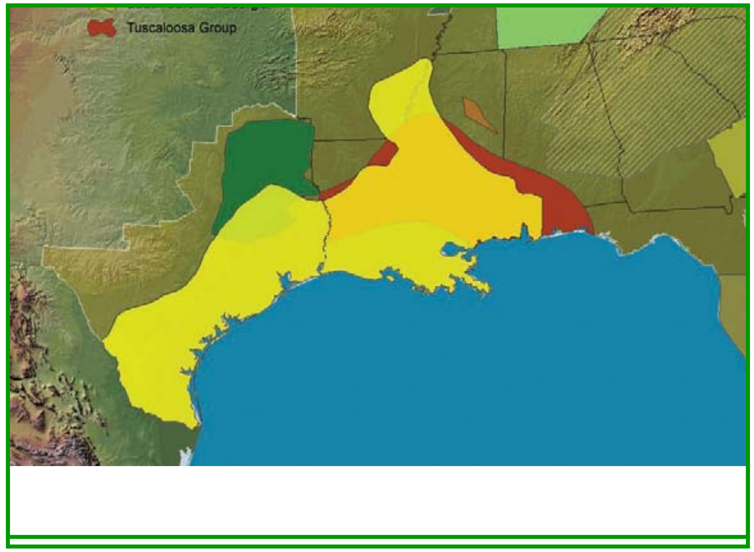
Pipeline leakage

- How large to present a threat; where; how?

Induced seismicity/faults

- Maximum sustainable reservoir pressures?
- Faults posing greatest risks?

Case II: TX-LA Gulf Coast

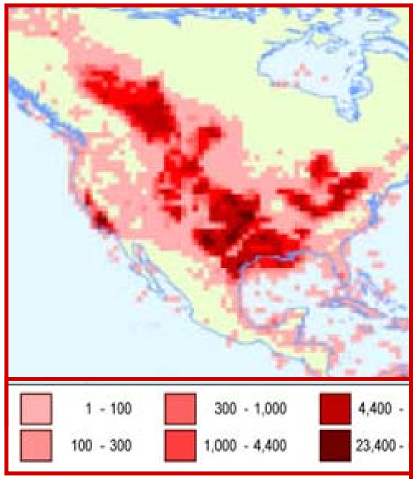


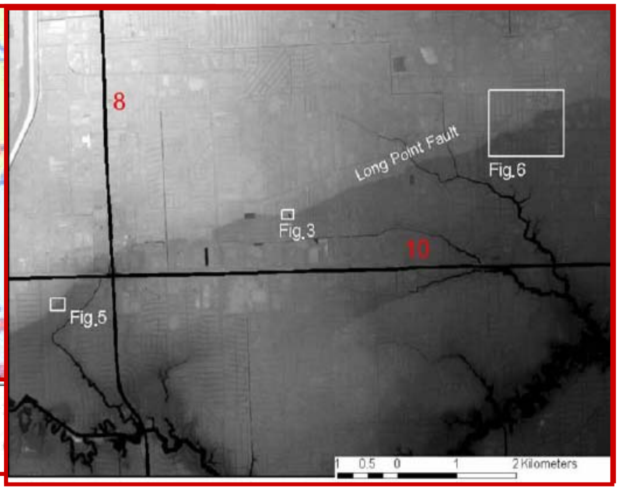
General
- Many large point sources, some pure
- Very large capacity (177-710 Gt for SF)
- World-class geological knowledge

ICE components
- Many potential reservoirs and seals
- High injectivity, high capacity
- Evidence of geological effectiveness

Central hazards
- V. high density of deep wells
- Mapped faults
- Groundwater risks

Risk coefficients – varies spatially
- Low - high population density
- Some faults reach the surface
- Many wells into deep targets
- Effectively aseismic, but mechanical risks





Special thanks to the SECARB & The Bureau of Economic Geology

An alternative prioritization could be proposed for other cases (e.g., Texas GOM)

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Prioritization uses expert knowledge and can be advised by science and experience

A protocol for the Gulf coast should focus on wells, wells, and wells

Due diligence could be met through aggressive site characterization, targeted monitoring, and simple mitigation strategies

Atmospheric release hazards	**Groundwater degradation hazards**	**Crustal Deformation hazards**
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Atmospheric release
- Pipeline leakage maxima?
- Location of unmapped/abandoned wells?

Well leakage and failure
- Maximum rates, under what circumstances?
- Maximum injection pressures?
- Deep wells intersecting sensitive groundwater areas?

Pipeline leakage
- How large to present a threat; where; how?

Fault slip and leakage
- Maximum sustainable reservoir pressures?
- Faults posing greatest risks?

The monitoring suite design and integration should focus on the hazards

Some approaches are obvious – others may have limited value in understanding hazards

Well configured to hazards

Geomechanical/Seismic
- Microseismic arrays
- Down-hole tilt
- Strain/pressure gauges

Well leakage and failure
- Aeromagnetic surveys
- Well-head sniffers/sensors
- Overlying unit pressure sensors

Not so obvious

Deep arrays
- Cross-well tomography
- VSP

Surface arrays
- LiDAR/FTIRS
- Soil gas flux chambers
- Atmospheric eddy towers

In all cases, real-time integration will provide clear understandings with the smallest M&V suite

A two-phase technical program can help provide insight needed to develop CCS protocols

First, simulations should provide constraints on CCS operating conditions

Second, a field program must substantiate these constraints

The program should focus on EARTH & ATMOSPHERIC HAZARDS of greatest relevance and provide:

- **If CO_2 leaks, what's the groundwater impact?**
- **Will large earthquakes occur due to CO_2 injection?**
- **Can our pipeline be routed in a way to minimize risk?**

Bounding analyses and simulations are necessary but not sufficient to create broad protocols

Conclusions

Operational protocols will help CCS deployment

- **Help guide regulations, standards**
- **Help gain public acceptance**
- **Help operators make decisions**

Hazards are the key

- **Provide decision-making framework**
- Flexible **to local geology**
- **Guide planning monitoring**
- **First step in risk quantification**

The map is not the territory
Alfred Korzbyski

The E&A hazards and need for protocols leads to a few important questions

•What is the technical basis for developing a risk hierarchy? How can that basis be improved?

•If wells represent the greatest risk, how can that risk be quickly characterized, quantified, and managed?

•If geomechanics represent substantial risks, what are the minimal data necessary to properly characterize those risks

•What science is necessary to understand the potential risks to fresh groundwater?

•What is the least monitoring necessary to serve the needs of all stakeholders?

The full list of E&A hazards suggests a need to rank, quantify, and respond to risk elements

This suggests the need for PROTOCOLS to inform operators and regulators on what actions to take for preparing a site. Given the lack of empirical data, other approaches are needed.

Use of analogs
- **Industrial analogs (NG storage)**
- **Natural analogs (HC systems, CO_2 domes)**

Simulation
- **Key features & processes**
- **Must be accurate, but not unduly complex**

Lab experimentation
- **Focus on most relevant problem**
- **Experimental design is key**

Scenario development
- **Max/min cases can be defined and tested**

Risk assessment methodology
- **Requires integration of results**
- **Some probabilistic methods as approp.**

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Iteration

Integration